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# THE POP-UP BUOY (PUB)

by

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ABSTRACT

The Pop-Up Buoy (PUB) was conceived as a practical means to implement a real-time telemetry link between a satellite and instruments beneath the ocean surface. It is a self-contained module, tethered to a moored sub-surface buoy, and capable of propelling itself up and down between the ocean surface and a submerged rest station. Most of its life is spent submerged, secure from storms and surface traffic, while storing data sent from remote sensors via an acoustic link. At pre-determined times of satellite passage, it rises to the surface for a brief transmission. If a storm is sensed by pressure fluctuations the transmission can be postponed or cancelled. Typical low data rates, e.g., only 3000 bits every 3 days in the acoustic tomography application, can be handled with infrequent transmissions. Energy for propulsion is then so small that a two-year life system may be packaged in a compact unit. A PUB sized for tomography has the form of a 56 cm sphere with small appendages and weighs 104 Kg (230 lbs). The design of this unit is described.

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# SECTION 1

# INTRODUCTION

## Background

We first conceived the Pop Up Buoy as a vital link in a future Ocean Acoustic Tomography Network. The heart of this network would be an array of sound sources and receivers moored deep in the ocean and spread over a broad area. Perturbations in the time required for sound to travel between these units can be processed to yield the fluctuations in large scale oceanic sound velocity, temperature and density structure. If these measurements could be telemetered to shore-based computers within a few days then real-time monitoring of ocean weather would be practicable. For a discussion see Munk and Wunsch (1979).

Long distance underwater acoustic telemetry requires energy supplies which seem enormous in the context of conventional underwater installations. Spiesberger and Worcester (1979) show that a typical unit only 1000 Km from a shore station might require 940 KWH over two years. A lithium battery pack to supply this much energy would weigh over 6000 lbs and cost well over $100,000. Nuclear sources are expensive and fraught with political sensitivities, and conventional batteries would be too cumbersome and unreliable in the size required. Techniques will be found to compress the data telemetry requirements and hence the energy supply; but it seems obvious that we should look for a more attractive alternative to underwater acoustic telemetry for applications involving long duration installations distant from shore.

UHF radio telemetry to a satellite from a buoy moored adjacent to a tomography receiver would involve far less energy. Buoys transmit to the NOAA satellite/ARGOS data collection and location system routinely at 400 bits/sec using tens of watts

radiated power. Using this system in accordance with standard procedure, 12 one-second bursts during a single 8-minute satellite pass would dump three days' accumulated tomography receiver data* for about 1/3 watt-hr, assuming no repetitions. In two years this transmitter would consume on the order of 0.1 KWH. An acoustic telemetry data link between the tomography receiver and the buoy would require on the order of 1 KWH in each unit (a two-way link is required to establish sound travel time so that the receiver clock drift can be computed at the shore base). However, the problem with the moored buoy-satellite link is not energy, but survival.

The mechanics of moored surface buoys in heavy seas is poorly understood; hence their design is often brutishly conservative (and expensive) and must always be highly empirical. On the other hand, to keep ship operating costs in balance the tomography network moorings should operate unattended for about two years, and each mooring should be producible at a cost of order $100,000. In shallow water some success has been achieved with sufficiently economical telemetry buoys, although a two-year unattended life for such buoys still seems far off. See for example the Georges Bank system described by Franklin et al (1978). However we need telemetry from points far at sea, and it's a fact of life that the proper design of a moored surface buoy system is critically dependent upon the depth of water in which it is moored. The National Data Buoy Program

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* each burst contains a maximum of 256 data bits (see ARGOS User's Guide)
three days worth of data are assumed to involve less than 3000 bits including:

1250 bits: 10-bit arrival time perturbations of 5 multipath pulses from each of 25 sources

1250 bits: 10-bit amplitudes of 5 multipath pulses from each of 25 sources

125 bits: 5-bit source ID words tagging each of 25 sources

40 bits: absolute time over 5 years to better than 1 ms resolution

(NDBP) experience indicates that only large systems beyond our means, such as the 10+-meter Discus Buoys or 6-meter NOMAD (boat-hull) Buoys, have been able to survive for two years in the deep North Atlantic and North Pacific Oceans. Kerut and Haas (1979) review the NDBP experience. Zimmerman (1979) reports that even the large successful buoys occasionally capsize in a storm. Vandalism and collision are also significant problems except in areas distant from shipping lanes and fishing grounds. A surface telemetry buoy to meet our requirements is just not available and could only be developed at a very high cost and on a very uncertain schedule.

But why should we maintain a surface buoy when we need only spend less than ten minutes every three days in communication with a satellite? Why not build a device which remains submerged between transmissions at a depth safe from storms and passing ships. While submerged it could receive and store data from the tomography receiver via a hard wire or acoustic link. A clock and a stored satellite pass ephemeris can indicate the proper times to ascend and transmit. Also, a pressure sensor can be included to detect surface storms and thereby warn our device to stay submerged until the next pass. We call this device a Pop Up Buoy (PUB).

This report describes our PUB design study carried out under the auspices of the ONR-funded Ocean Acoustic Tomography research program at M.I.T. and Draper Lab.

## Design Study

Purpose: The purpose of our study is to create and evaluate a preliminary design of a Pop Up Buoy (PUB). The PUB is to remain submerged, safe from storms and passing ships, at all times except once every three days when it must ascend to the surface to transmit a 3000-bit data message to a low altitude NOAA satellite.

Design Objectives:

1. Low Cost: The PUB plus its deep ocean mooring must cost less than $100,000 in small lot production.

2. Deployability: The PUB and its mooring must be readily deployable by marine technicians experienced in handling standard deep ocean moorings.

3. Long Life: The PUB should be capable of operating unattended for two years between routine recoveries and refurbishments.

New Technology: The only significant new technology involved in the PUB design is resident in the mechanical means to achieve vertical mobility for minimum energy cost and consistent with acceptable behavior on the sea surface.

Approach: Our approach has been to conceive, analyze, layout, and evaluate competitive mechanisms to achieve vertical mobility. In each case we have assumed the same basic spherical hull shape. While this shape is probably not optimum for antenna pointing, it has important advantages: low cost for high pressure integrity and most easily-modelled hydrodynamic behavior.

Results: Our PUB is a self-contained module, tethered to a moored subsurface buoy, and capable of propelling itself up and down between the ocean surface and a rest station at 45 meters depth. The energy stored for propulsion is small enough (under 2 KWH) that a two-year life system may be packaged in a small unit, basically a 22-inch (56 cm) sphere with small appendages, weighing 230 lbs. Development of this device to operational status would require four years at the modest level of effort sustainable in the oceanographic community.

# SECTION 2

# PRELIMINARY SYSTEM DESIGN

Figure 2.1 shows an outline drawing of the PUB. This drawing also shows to a much smaller scale the subsurface mooring to which the PUB would be tethered. The PUB would operate between the sea surface and the subsurface buoy at a nominal depth of 45 meters; however it can survive 900 meters water pressure, a conservative requirement to allow for an unlikely extreme current pushing down a deep ocean subsurface mooring. The PUB has a net buoyancy of 223 N (50 lbs) fully submerged and 200 N (45 lbs) when the antenna is out of the water. Total deck weight is 1024 N (230 lbs).

## 2.1 Mode of Operation

The PUB is a buoyant self-contained module, tethered to a moored subsurface buoy, capable of propelling itself up and down between the ocean surface and the submerged nest. This is accomplished by winding and unwinding the tether line on a spool mounted on the PUB. In order to maintain tether line tensions within a prescribed range, to prevent line damage, a large spiral power spring is inserted in series between the spool drive motor and the spool. This spring will automatically wind several meters of line onto the spool as the buoy drops into the trough of a wave, or pay out several meters of line when the buoy rides the crest of a wave. As a result of this feature, the motor may be electrically de-energized and mechanically locked both while riding the sea surface and while at nesting depth. During these periods no energy would be consumed by the motor. Angle sensors on the spring arbor and drum indicate spring position and therefore

the related tether line tension. At the surface, if tension falls below the minimum prescribed tension due to slackening sea currents the motor will be energized to haul in enough line to restore nominal tension. Should tension build up above the maximum prescribed tension due to increasing currents, the motor would be mechanically unlocked to provide more scope. If all the line is out and the spring is at its maximum tension position the potential for overstress exists. In this case data transmission could be terminated and the PUB winched down to its protective nesting depth. Note that the motor consumes energy only during descent stage or while hauling in line. Ascent is accomplished passively by the net buoyancy force when the drive motor is unlocked. Ascent speed is controlled to about 0.3 meters per second by switching the motor to its braking (generator) mode. Although it is feasible to store a useful fraction of the electrical energy during ascent, we have not taken advantage of this feature in our energy budget because the attendant complexity may not be warranted.

The PUB would spend most of its time hauled down to the subsurface buoy, safely below storms and surface traffic. While "nested" in this position it would collect data via an acoustic telemetry link with nearby or remote sensors. We have presumed an acoustic link so that the PUB may be mechanically separated from the sensors it services, and so that the PUB's mooring may be separated from the sensor moorings. In this manner we can simplify the PUB's interfaces and make it a more versatile system. A hardwire link is possible, however, and could be provided by modification of the PUB hardware.

For the preliminary design we have also presumed an RF transmitter and antenna suitable for communication with a low altitude satellite. Communication with a synchronous satellite such as GOES would provide an advantage we don't need (constant visibility) at a significant cost in terms of transmitter power and lower data rate.

## 2.2 Layout of PUB

The instrument spherical housing is comprised of two 22-inch diameter aluminum-spun hemispheres with o-ring seals. This type of housing design is well-proven and reasonably economical to fabricate. At the sea surface the spherical housing would normally be riding part way out of the water, exposing a microwave antenna. The physical size and shape of an antenna depends on many factors, including transmission frequency, field pattern, efficiency and power required.

CHU Associates has built an antenna for two-way communication with the GOES satellite (401 & 469 MHz). This antenna is a cone 100 cm high with a base diameter of 44.5 cm. It is used with a 40 watt transmitter. In contrast, a meteorological data buoy system, transmitting 1.5 watts to the TIROS-N satellite, uses an antenna in a housing approximately 10 cm diameter and 38 cm high. It is also possible to consider a flat antenna applied to the buoy's surface. This would minimize drag and buoyancy effects. The antenna shown in Figure 2.1 is simply an estimate of the size and shape which we presently view as reasonable for low power transmissions to a low-orbiting satellite such as the TIROS-N or NOAA. The smallest possible antenna is desired to optimize stability at the sea surface and to minimize buoyancy and therefore the winch power requirement.

All electronics and battery power required for the PUB are housed inside the instrument sphere. This includes electronics to operate the winch motor, a satellite transmitting chassis, acoustic telemetry electronics, power regulators, batteries, and clock.

The major power user is the winch motor. Two hundred cycles to the surface are accomplished with 10 pounds of lithium batteries.

The winch assembly described in more detail in Section 3 is a separate sub-assembly mounted below the spherical housing. Electrical communication between the winch assembly and instrument housing is accomplished by using commercially-available underwater connectors and cables.

In general, surfaces which interface with sea water are corrosion-resistant and protected from biofouling using proven paint systems. Plastic materials are used whenever practical.

## 2.3 Protection from Biofouling

The careful selection of materials and paint systems has proved successful for corrosion and biological fouling protection of our instruments. Several protective systems were recently tested for endurance and effectiveness over a period of 18 months.

For the PUB application three materials providing extremely good anti-fouling protection are NOFOUL[1] rubber, Organo-tin paint[2] and Gloucester 515 special Red A.F. Paint[3]. These protective materials can be applied directly to our plastic substrates. NOFOUL rubber can be applied to metals after special priming. Prior to application of the anti-fouling paint most metal substrates require an undercoat specially designed to adhere well. The undercoat also provides a dielectric film to prevent galvanic corrosive action between the metal substrate and the antifouling topcoat.

Recessed regions with limited water access, though fully flooded, have not been fouled in our tests. We have also found that rollers prevent biological growth on cables. Those parts of the winch assembly exposed to seawater would be doubly protected, both by antifouling paints and by their enclosure. The tether line would not require an antifouling

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NOTES: (1) B. F. Goodrich Company
(2) International Paint Company, SPC-4 or Micron-22.
(3) 70.2% Cuprous oxide phenolic paint

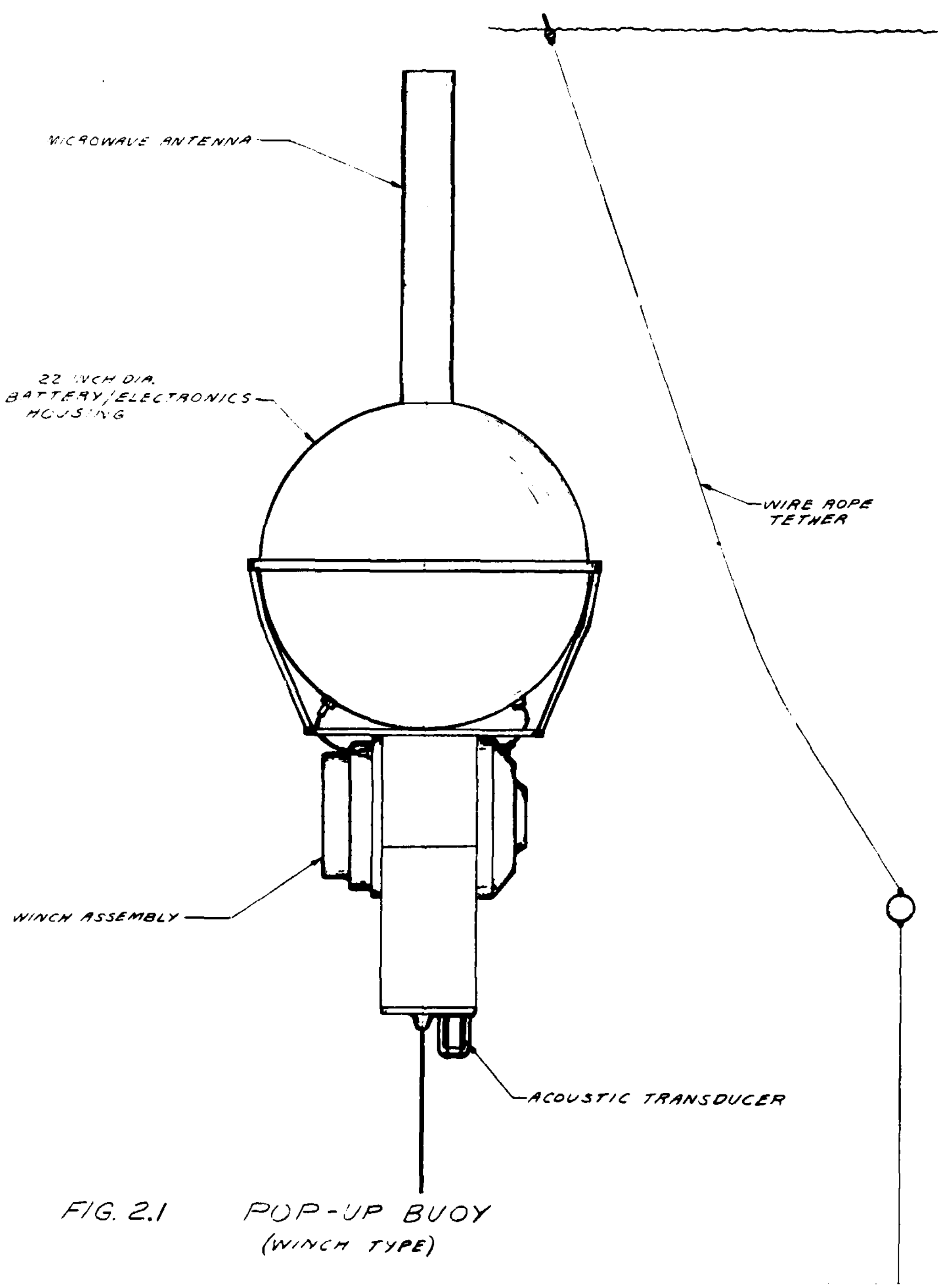


FIG. 2.1 POP-UP BUOY
(WINCH TYPE)

coating. It would be protected by its enclosure, the level wind and guide roller action, and by rubbing on the spool and within the exit fairlead.

## SECTION 3

## PRELIMINARY WINCH DESIGN

Figure 3.1 shows a design layout of the winch subassembly. The center section of this assembly with its casual closure is freely flooded with seawater. It contains the spool, tether line, level-wind mechanism and fairlead. A cylindrical housing on one side of the assembly contains a motor, gear train, and solenoid-operated latching mechanism. A second cylindrical housing on the other side contains a power spring and angle sensors. Both cylindrical housings are filled with high dielectric oil. Flexible diaphragms maintain the oil in pressure equilibrium with the seawater environment. Therefore, no pressure differential will exist across the cylindrical housings or across the rotary o-ring seals which separate the housings from the spool section.

### 3.1 Spool Section

The spool section of the winch subassembly is made up of two 3/4" thick Noryl[R*] resin side plates spaced and aligned with four Noryl stand-off spacers. Noryl was selected because of its high strength and stability, and low swelling and water absorbtion characteristics when exposed to sea water. It has relatively low weight and is readily paintable. The design lends itself to the line boring of many holes in the two side plates.

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*R REGISTERED TRADE MARK - GFNERAL ELECTRIC COMPANY

A Noryl spool having a 7" hub and 9½" diameter flanges is mounted to a hollow 316 stainless steel axle which is ball bearing-supported between the two side plates. The axle ends project into the oil-filled cylindrical housings. Dynamic o-ring seals segregate the oil-filled volumes from the seawater. The spool holds 74 meters (242 ft) of 3/16" outside diameter plastic-jacketed wire rope tether line. The line is long enough to enable the PUB to hold its antenna above the ocean surface in a uniform current above the subsurface buoy of 0.6 meters/second. The line is fed off the spool between two rollers mounted on a block riding on a 316 stainless steel level-wind screw having a 0.675-inch pitch. The level-wind design is similar to that found on many winching units. Commercially available Delrin spur gears having a ratio of 3.6:1 couple the spool hub to the level-wind screw. Plastic journal bearings, capable of operating in seawater, support the level-wind screw and spur gear shafts. The wire leaves the level-wind rollers and is then guided by a three-roller assembly through a fairlead at the lower end of the assembly. The fairlead is integral with the lower closure which is made of flexible polyurethane. This will minimize the chance of damaging the tether line while PUB is bobbing at the sea surface. The remaining sides of this section will be casually enclosed with Noryl plates to keep any debris from fouling the contained mechanisms. Biofouling in this dark, nearly closed volume is easily prevented by means of paint systems which have been verified in field demonstrations.

### 3.2 Motor Drive Section

A Noryl cylindrical housing is attached to the spool section side plate. This oil-filled housing contains a drive motor, gearing, locking wheel, pawl, solenoids, and associated parts. O-ring seals isolate the oil-filled space from the seawater environment. A flexible diaphragm compensates for volume

changes due to temperature variations and maintains pressure equilibrium with the outside environment.

A brush-type D.C. torque motor was tentatively selected to drive the spool. This type of motor has been successfully used in an oil environment; however, we plan to study the advisability of using a brushless torque motor. The selected motor has a rated peak torque of 6 ft-lbs. The maximum torque which must be delivered to the spool is 30 ft-lbs. A 16:1 gear reduction between the motor and spool allows the motor to normally operate at less than 30% of peak torque, which is in the region of maximum operating efficiency. The motor, through two passes of commercially-available stock spur gears, drives a shaft which passes through the hollow spool axle described above. This shaft drives a power spring, to be described in a later section, which in turn drives the spool.

A six-toothed locking wheel is mounted on the motor shaft. Since the tether line is always in tension, a torque always exists on the locking wheel. When the pivoted pawl engages a tooth in the locking wheel, the shaft is immobilized. When the pawl is disengaged, the shaft is free-running. The pawl is actuated by electrically pulsing either the latching or unlatching solenoid. A bi-stable extension spring will hold the pawl in the desired position, obviating the requirement of continuously supplying power to a solenoid.

### 3.3 Power Spring Section

The power spring is a spiral wound .050" x 1½" x 52' long strip of flat spring steel. Its inner end is secured to a 1½" diameter arbor and its outer end is secured to the inside of a 9" diameter drum. The arbor is coupled to the spool and the drum is coupled to the motor via the inner shaft and the spur gears. The spring has a 19-turn travel range which corresponds to 35 feet of tether line travel. A 38-lb. pull on the line is required to completely wind the 19-turn spring. The load-deflection curve is nonlinear for this type of spring. Angle sensors mounted on the spring arbor and drum

constantly track the number of turns travelled with respect to the housing. This information relates to the tension condition of the spring and is used to maintain the tether line tension with the prescribed limits in spite of the waves and variable current.

When the PUB surfaces, the motor is mechanically locked when the sensed angles indicate 31 lbs. tension in the tether line. The motor will remain locked between 21 and 36 lbs. tension, which corresponds to a 20 ft. (± 10 ft.) change in line length. Should the sea current change or should an unusual sea state tend to cause the spring to move out of this range, the motor will be unlocked and allowed to reposition the spring within the desired limits.

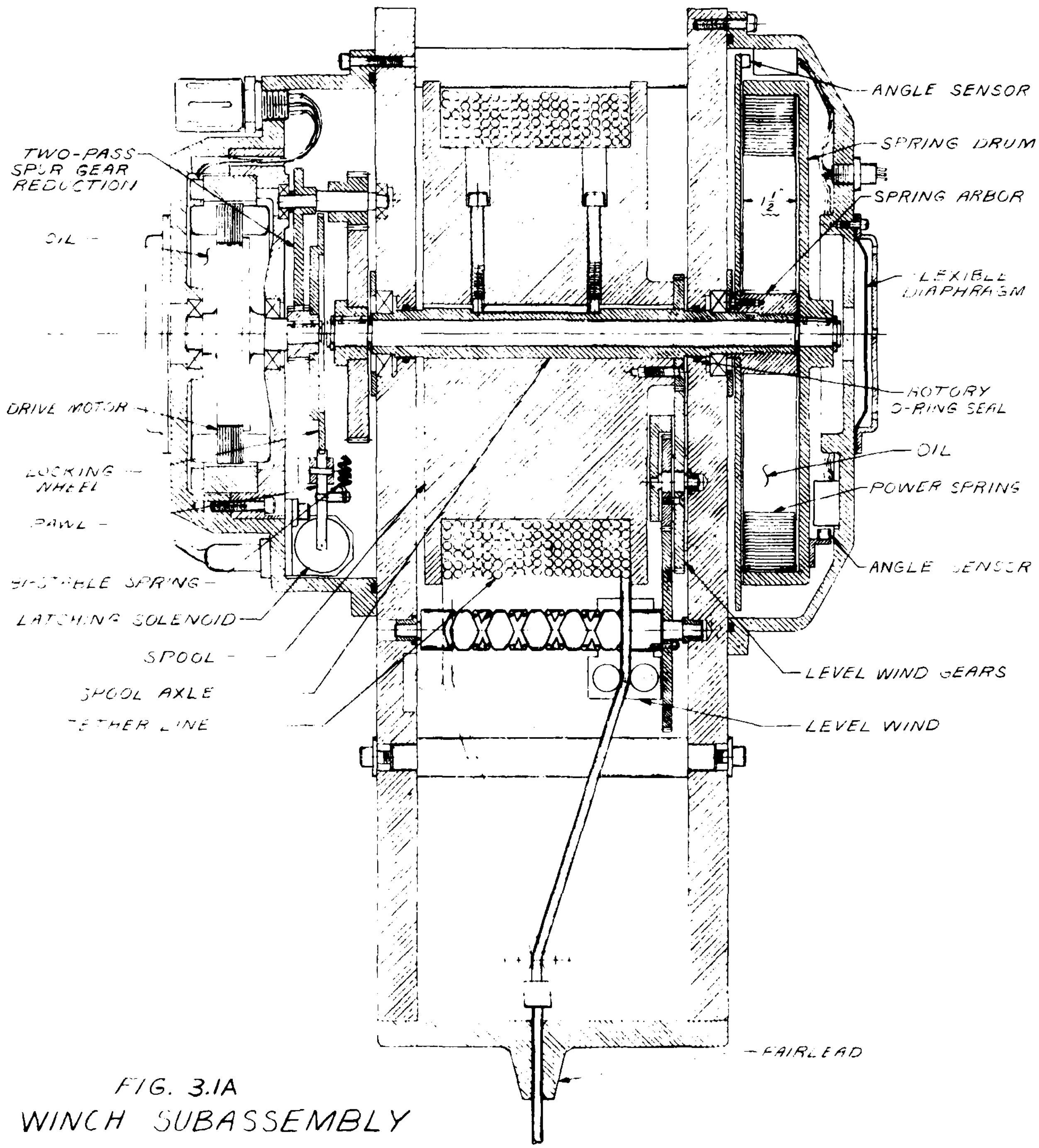



FIG. 3.1A
WINCH SUBASSEMBLY

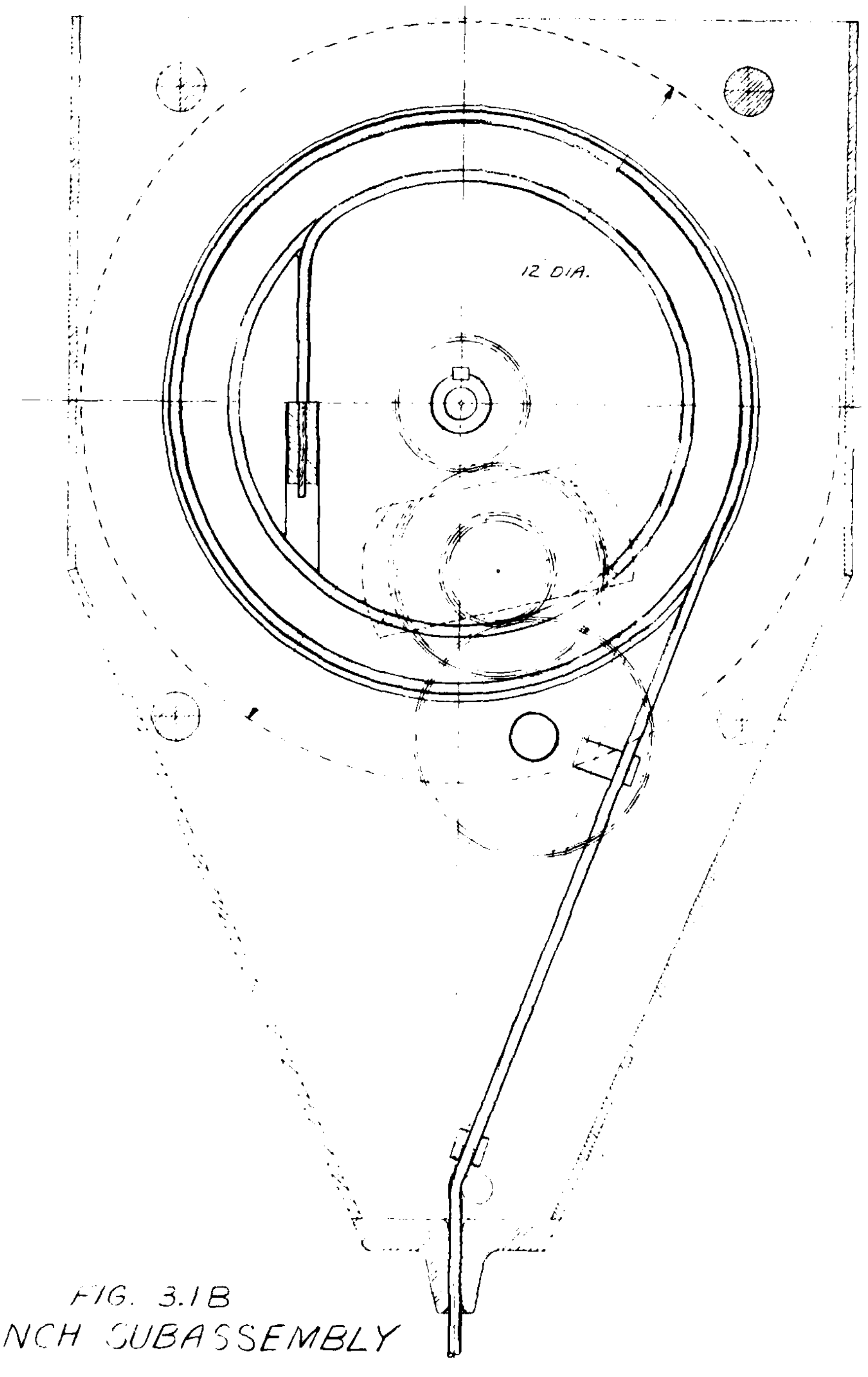



FIG. 3.1B
WINCH SUBASSEMBLY

## SECTION 4

## ENERGY ANALYSIS

Analysis of the dynamic response and the energy required for the PUB to propell itself up and down between the ocean surface and a submerged nest is presented in this section. Depth of the submerged nest and the length of tether between the nest and the PUB on the ocean surface are required for energy calculations.

### 4.1 Determination of the PUB Rest Depth

It is desirable to moor the PUB at a minimum possible depth for the smallest possible winch and the least energy requirement. On the other hand this minimum depth ($h_{min}$) must be large enough for the moored system to survive wave/storm damage. Assume a strawman PUB (along with its mooring system) as shown in Figure 4.1. Dynamic computer simulations using the lumped parameter formulation of CHHABRA 1976 were run to study the survivability of this system. Following was assumed for the first set of runs.

a) Zero mean current profile

b) Surface wave forcing from a wave of crest-trough height = 21 m and a frequency = 0.42 radians/sec. (This corresponds to a sea state = 8)

c) The PUB and the subsurface float are assumed to be lumped together at one node.

<u>Simulation Results</u>

Undamped Natural Frequencies of the system:-

Longitudinal = 0.36 radians/sec
Pendulum = 0.03 radians/sec

Table 4.1 lists the run number; depths of the top node (PUB and subsurface float); maximum and minimum tensions below this node; safety factors in the 6.4 mm (¼") wire, maximum tensions in the 4.8 mm (3/16") wire and the safety factors in this wire.

| No. | PUB Depth (m) | TENSION BELOW PUB/S.S. Float LBS* | | S.F. 6.4mm Wire | MAX. TENSION in 4.8mm (3/16") Wire | S.F. 4.8mm Wire |
|---|---|---|---|---|---|---|
| | | max | min | | | |
| 1 | 48.9 | 2735 | 1840 | 2.5 | 2025 | 2.1 |
| 2 | 38.8 | 2792 | 1768 | 2.4 | 2082 | 2.1 |
| 3 | 28.1 | 2862 | 1675 | 2.4 | 2152 | 2.0 |
| 4 | 15.9 | 2954 | 1538 | 2.3 | 2244 | 1.9 |

TABLE 4.1

It should be noted that the weight of components below the subsurface float is 1268 lbs, which is lesser than the minimum tension (Case 4 - 1538 lbs) below the float. Hence from the survival point of view any of the four runs presented in Table 4.1 might be acceptable. For the second set of runs the PUB and the subsurface float are assumed as two separate nodes separated by 0.3m of wire. Table 4.2 lists the run number; depths of the top node (PUB); maximum and minimum tensions below this node and the safety factor in the tether.

*To obtain newtons multiply by 4.45

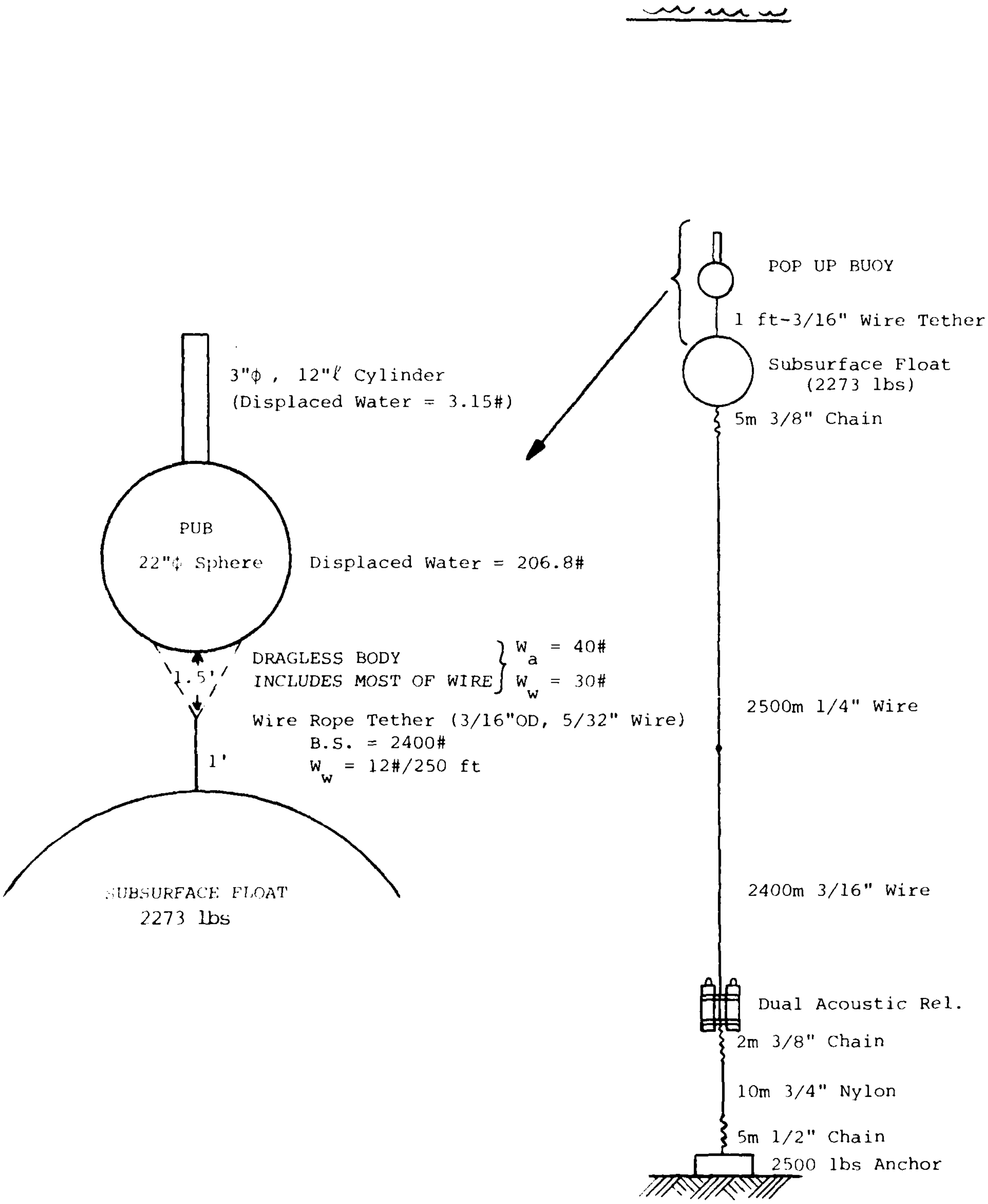



Figure 4-1 - PUB Mooring System

| No. | PUB Depth (m) | TENSION BELOW PUB LBS | | Safety Factor in Tether |
|---|---|---|---|---|
| | | max | min | |
| 1 | 15.9 | 112 | Negative | 21 |
| 2 | 28.1 | 101 | Negative | 24 |
| 3 | 38.8 | 93 | 5 | 26 |
| 4 | 48.9 | 86 | 13 | 28 |

TABLE 4.2

Hence, if we want to keep some tension in the tether (wire between PUB and subsurface float) while PUB is at its rest depth, the minimum rest depth should be approximately 40 meters (Case 3 of Table 4.2). To overcome this limitation and in order to maintain tension in the tether line at all times a large, spiral power spring is inserted in series between the gear box and the spool. Function of this spring has been described elsewhere in this report. The minimum depth can now be chosen to be 30 meters.

Our target depth ($h_{tar}$) for the PUB at rest should be $h_{min}$ plus allowance for setting errors.

A 5000m length of wire (4.8mm or 3/16") under a tension of 1800 lbs stretches an amount approximately equal to 20 meters. Assuming an uncertainty of 10% in the knowledge of stretch characteristics we obtain a two meter error due to stretch. Also assuming that the depth at the point of anchor implant can be determined to within 10 meters and that the total length of the mooring components can be determined to within 5 meters; we can conservatively put the setting error

to $\pm 15$ meters. Hence;

$$h_{tar} = 30 + 15 = 45 \text{ meters}$$

## 4.2 Determination of the PUB Maximum Depths

Next, we need to determine the maximum depth at which the PUB might be required to perform all its functions. This maximum operational depth ($h_{maxo}$) is obtained by adding $h_{tar}$ , setting error, and the vertical excursion due to typical currents. This depth will design the winch and the battery-pack. The pressure capability of the PUB will be determined by the excursion at extreme currents.

Excursions of the PUB were found for six different current profiles. Static Analyses were performed for this study. Profile #1 is zero current. Profiles #2 and #3 are shown in Figure 4.2; and profiles #4, 5 and 6 are uniform currents of 30, 60 and 90 cm/sec from top to bottom. Vertical and horizontal excursions of the PUB are listed for these six profiles in Table 4.3.

| No. | Vertical Excursion (m) | Horizontal Excursion (m) | Remarks |
|---|---|---|---|
| 1 | 0 | 0 | Zero |
| 2 | 0.1 | 21.0 | Typical Profile A |
| 3 | 0.6 | 78.2 | Typical Profile B |
| 4 | 82.2 | 754.4 | Extreme A |
| 5 | 842.2 | 2358.6 | Extreme B |
| 6 | 1949.5 | 3458.2 | Extreme C |

TABLE 4.3

From these calculations it seems that the vertical excursions under typical conditions are small compared to

the 60 meters ($h_{tar}$ + setting error) depth. Hence; $h_{maxo}$ = 60m.

To determine the maximum life time depth ($h_{max}$) which governs the pressure capability of the PUB, we chose excursions from Case 5 (uniform current of 60 cm/sec) of Table 4.3 above to give

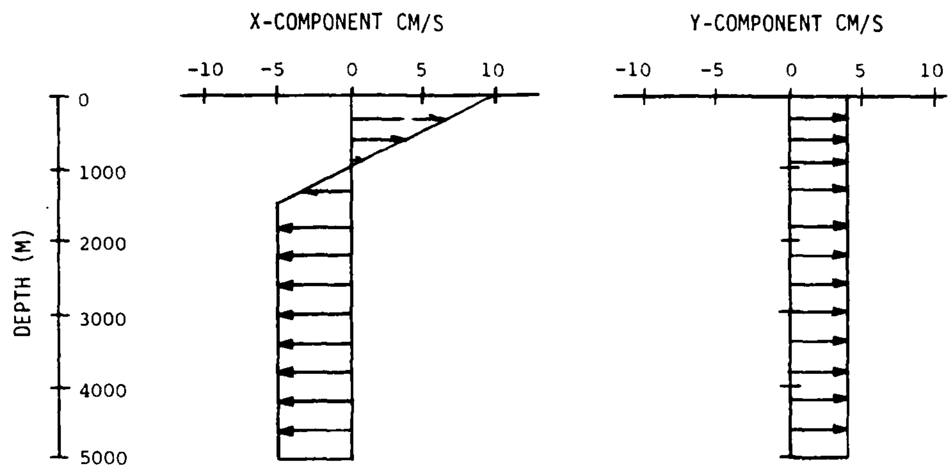
$$h_{max} = 60 + 842 = 902m$$

This depth is for a very extreme 60 cm/sec current all the way to the bottom.

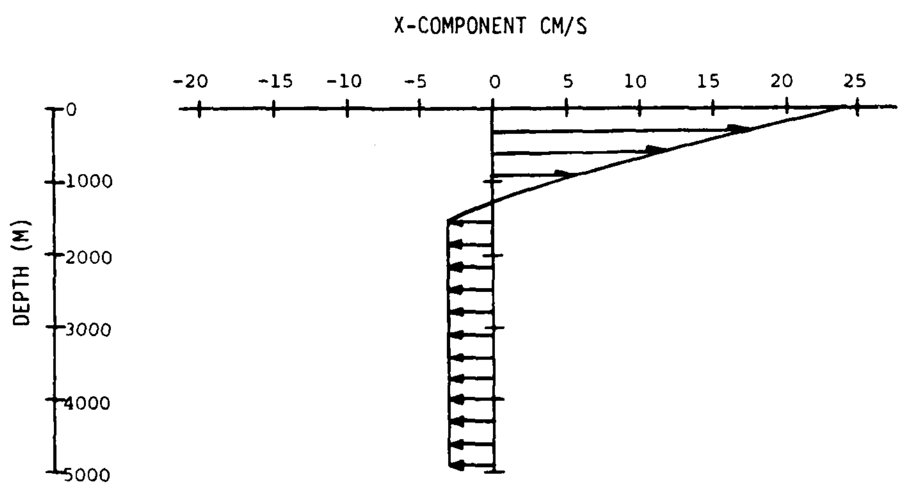
## 4.3 Determination of the Tether Length Required in the Winch Type PUB

Static Analyses of the four node system shown in Figure 4.3 were done for various lengths ($\ell$) of the tether, three current profiles ($\overline{V}$) and two depths (h) of the subsurface float. Results from these analyses are tabulated in Tables 4.4 through 4.7. Tables 4.4 and 4.5 have the subsurface float at a depth of approximately 40 meters. Table 4.4 is for a weak current profile (9.1 cm/sec, uniform with depth) and Table 4.5 is for a stronger current (45.7 cm/sec from surface to the subsurface float and 9.1 cm/sec below it). Tables 4.6 and 4.7 have the subsurface float at a depth of approximately 80 meters. Table 4.6 is for the same current profile as Table 4.4 and Table 4.7 has a current of 61 cm/sec from surface to the subsurface float and 9.1 cm/sec below it. These results are also presented in Figures 4.4 and 4.5. Buoyancy (weight of water displaced) of the PUB and the tension below the PUB is plotted against the length $\ell$, in Figure 4.4. Figure 4.5 shows the configurations of the tether between the subsurface float and the PUB for Case 1 (Table 4.4) and Case 4 (Table 4.7).

The maximum length of the tether ($\ell$) required in the winch PUB can be determined from Figure 4.4. For $h_{maxo}$ (maximum operational depth of the submerged nest) of 60m




PROFILE #2 (TYPICAL A)




PROFILE #3 (TYPICAL B)

Figure 4.2 - Typical Current Profiles

| Case 1 - Current is constant from top to bottom = 9.1 cm/s | | | | | | |
|---|---|---|---|---|---|---|
| Length $\ell$(m) | Mass Water Displaced by PUB (kg) | Subsurface Float Coordinates(m) | | PUB Coordinates (m) | | Tension Below PUB (lbs) |
| | | Horiz(x) | Depth(h) | Horiz(x) | Depth(h) | |
| 36.6 | 96.3 | 64.8 | 40.6 | 65.1 | 2.0 | 61.17 |
| 38.1 | 95.2 | 64.9 | 40.5 | 65.1 | 0.5 | 58.76 |
| 38.7 | 75.1 | 66.3 | 40.9 | 67.7 | 0.2 | 14.61 |
| 39.6 | 72.0 | 63.7 | 41.2 | 70.7 | 0.2 | 7.68 |
| 57.9 | 71.3 | 66.2 | 41.0 | 99.6 | 0.2 | 6.14 |
| 76.2 | 71.2 | 66.2 | 41.4 | 104.9 | 0.2 | 6.01 |

TABLE 4.4

| Case 2-Current is 45.7cm/s on tether and 9.1cm/s below Subsurface Float | | | | | | |
|---|---|---|---|---|---|---|
| Length $\ell$(m) | Mass Water Displaced by PUB (kg) | Subsurface Float Coordinates(m) | | PUB Coordinates (m) | | Tension Below PUB (lbs) |
| | | Horiz(x) | Depth(h) | Horiz(x) | Depth(h) | |
| 36.6 | 96.3 | 86.9 | 40.9 | 92.8 | 2.9 | 61.29 |
| 38.1 | 96.3 | 86.9 | 40.9 | 93.1 | 1.4 | 61.29 |
| 39.6 | 90.0 | 84.6 | 41.1 | 92.5 | 0.3 | 47.39 |
| 41.2 | 80.9 | 86.6 | 40.9 | 100.5 | 0.3 | 27.52 |
| 42.7 | 78.8 | 85.9 | 41.2 | 102.9 | 0.3 | 22.95 |
| 45.7 | 76.3 | 84.2 | 41.2 | 107.1 | 0.3 | 17.34 |
| 48.8 | 75.0 | 82.7 | 41.2 | 110.3 | 0.2 | 14.44 |
| 57.9 | 73.3 | 81.4 | 41.2 | 119.1 | 0.2 | 10.97 |
| 76.2 | 71.8 | 79.4 | 41.2 | 130.8 | 0.2 | 7.63 |
| 91.5 | 71.0 | 79.0 | 41.0 | 139.3 | 0.2 | 6.02 |

TABLE 4.5

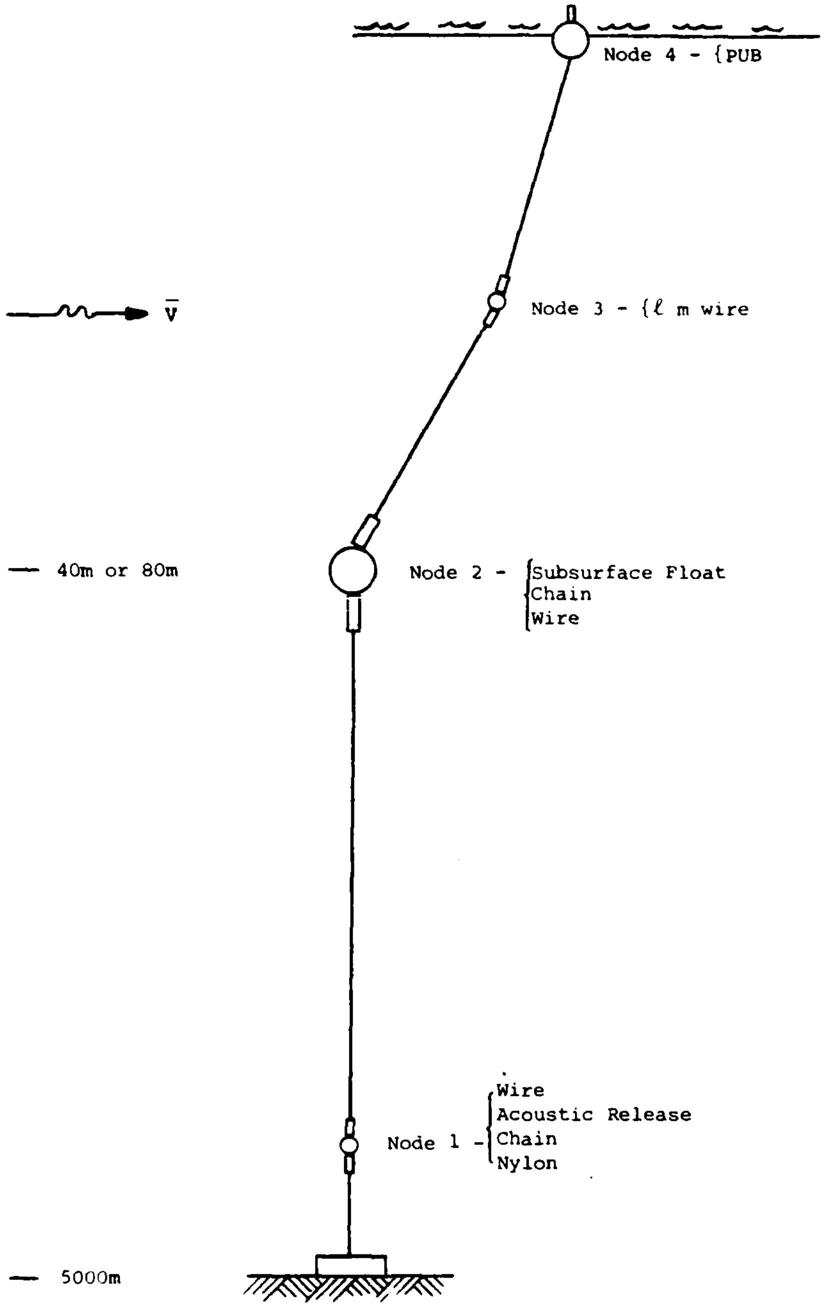



Figure 4.3 - Four Node Mooring System

| Case 3 - Current Constant from Top to Bottom = 9.1 cm/sec | | | | | | |
|---|---|---|---|---|---|---|
| Length $\ell$(m) | Mass Water Displaced by PUB (kg) | Subsurface Float Coordinates (m) | | PUB Coordinates (m) | | Tension Below PUB (lbs) |
| | | Horiz(x) | Depth(h) | Horiz(x) | Depth(h) | |
| 36.6 | 96.3 | 64.8 | 80.2 | 65.1 | 41.7 | 61.17 |
| 67.1 | 96.3 | 64.8 | 80.2 | 65.2 | 11.2 | 61.17 |
| 76.2 | 96.3 | 64.8 | 80.2 | 65.2 | 2.0 | 61.17 |
| 77.7 | 95.2 | 64.9 | 80.2 | 65.3 | 0.5 | 58.76 |
| 79.3 | 72.0 | 63.7 | 80.8 | 71.3 | 0.2 | 7.68 |
| 88.4 | 71.4 | 66.4 | 80.8 | 92.7 | 0.2 | 6.31 |
| 100.6 | 71.3 | 66.2 | 81.0 | 101.7 | 0.2 | 6.11 |
| 122.0 | 71.3 | 66.2 | 80.7 | 124.5 | 0.2 | 6.06 |

TABLE 4.6

| Case 4 - Current is 61 cm/s on tether and 9.1 cm/s below Subsurface Float | | | | | | |
|---|---|---|---|---|---|---|
| Length $\ell$(m) | Mass Water Displaced by PUB (kg) | Subsurface Float Coordinates(m) | | PUB Coordinates (m) | | Tension Below PUB (lbs) |
| | | Horiz(x) | Depth(h) | Horiz(x) | Depth(h) | |
| 76.2 | 96.3 | 101.7 | 80.9 | 117.0 | 4.5 | 61.56 |
| 79.3 | 96.3 | 101.7 | 80.9 | 117.3 | 1.5 | 61.56 |
| 82.3 | 85.9 | 102.7 | 80.8 | 124.8 | 0.3 | 38.77 |
| 88.4 | 78.8 | 97.2 | 81.1 | 132.2 | 0.3 | 23.32 |
| 97.6 | 75.7 | 94.3 | 81.3 | 143.0 | 0.3 | 16.59 |
| 115.9 | 72.9 | 89.0 | 81.3 | 160.4 | 0.2 | 10.73 |
| 137.2 | 71.6 | 87.0 | 81.1 | 181.0 | 0.2 | 8.24 |

TABLE 4.7

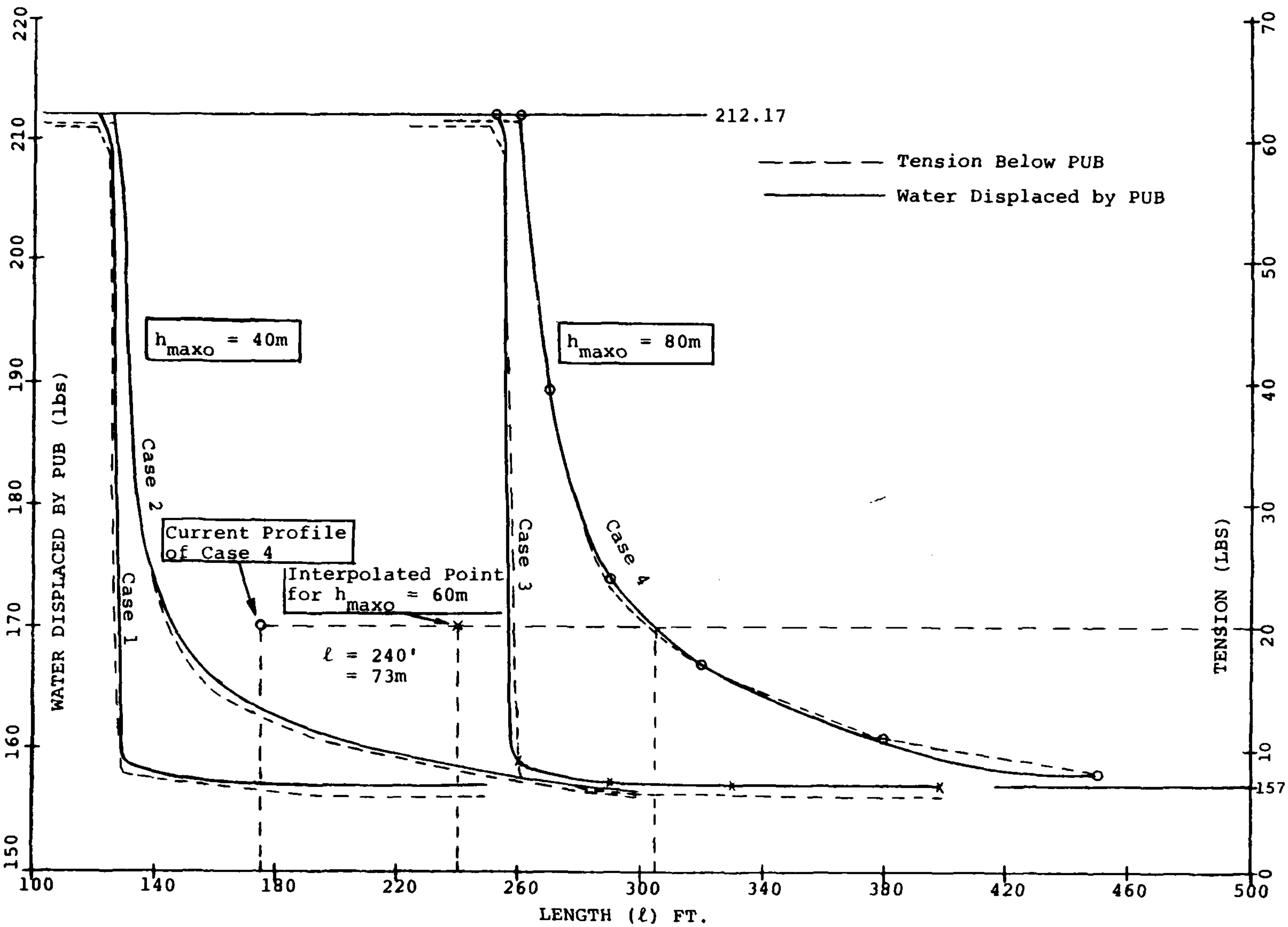



Figure 4.4 - Tether Length versus water displaced by PUB

and a maximum surface current of approximately 61 cm/sec; $\ell_{max}$ is 73m. This is determined as the length required for the severe Case 4 environment and for the deepest the subsurface float would be in the operational mode ($h_{maxo}$ = 60m) to maintain a mean tension of greater than or equal to 20 lbs (89N) below the PUB.

### 4.4 Evaluation of Competitive Design Concepts

Four approaches to the means of propelling and tethering the PUB were considered, but only two were promising enough and are presented here. These are the electric winch and the variable buoyancy approaches. Force diagrams for each configuration at different positions of its cycle have been presented for different environmental conditions. Energy/cycle for each case has been calculated. Some basic assumptions made in this study are:

- Nominal resting depth of PUB = 45m
- Minimum resting depth of PUB = 30m
- Maximum (operational) resting depth of PUB = 60m
- Maximum (survival) depth of PUB = 900m
- Ascent/Descent rate of the PUB ($\dot{z}$) = 30 cm/sec
- Maximum surface current under operational conditions is 61 cm/sec.

Electric Winch System

- Wire rope is immersed when it is on the spool
- PUB is 56 cm OD sphere; it has a 9 cm dia. and 76 cm long cylindrical antenna; it also has a winch enclosure 23 cm x 23 cm x 51 cm at the bottom
- Tether is 4.8mm (3/16") OD, and weighs 0.134 lbs/m in water.

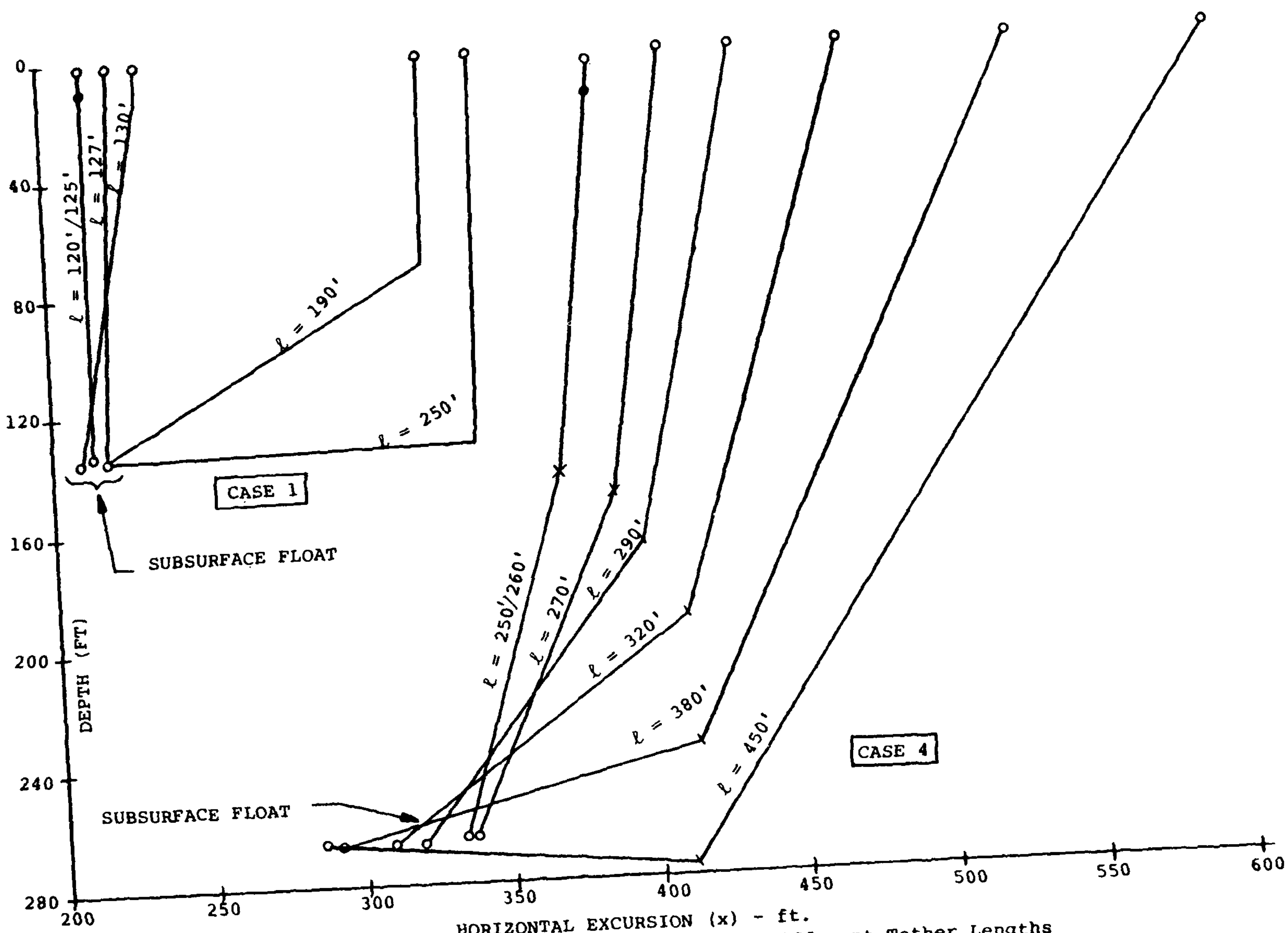



Figure 4.5 - Configuration of the Tether for different Tether Lengths

Force diagrams of the system at five locations under zero current, no waves and $\dot{z} = 0$ are shown in Figure 4.6 . Figure 4.7 shows force diagrams for zero current, no waves and $\dot{z} = \pm 30$ cm/sec. Figure 4.8 is similarly drawn for no waves, a surface current of 61 cm/sec, and $\dot{z} = \pm 30$ cm/sec. For a 100% efficient electric winch the work required/cycle for the three cases presented in Figures 4.6 through 4.8 is 12,282 Nm; 12816 Nm and 18,942 Nm respectively.

Variable Buoyancy System

- PUB is 76 cm OD sphere; it has a 9 cm dia. and 76 cm long cylindrical antenna; it also has a 28 cm dia. and 51 cm long enclosure for the bladder assembly.
- Tether is 61m of 3/16" chain weighing 66 lbs in water at the bottom of which is attached 174 lbs (wet) ballast chain.

Force diagrams of the system at four locations under zero current, no waves and $\dot{z} = 0$ are shown in Figure 4.9 . Figure 4.10 shows force diagrams for zero current, no waves and $\dot{z} = \pm 30$ cm/sec. Figure 4.11 is similarly drawn for no waves; a surface current of 61 cm/sec and $\dot{z} = \pm 30$ cm/sec. For a 100% efficient system the work required/cycle for the three cases presented in Figures 4.9 through 4.11 is 0; 2030 Nm; and 8637 Nm respectively. Also the maximum buoyancy change required in the PUB for a complete cycle is 165 N (37 lbs).

- Case 1; No Current; No Waves and $\dot{z} = 0$
- All Forces in Lbs

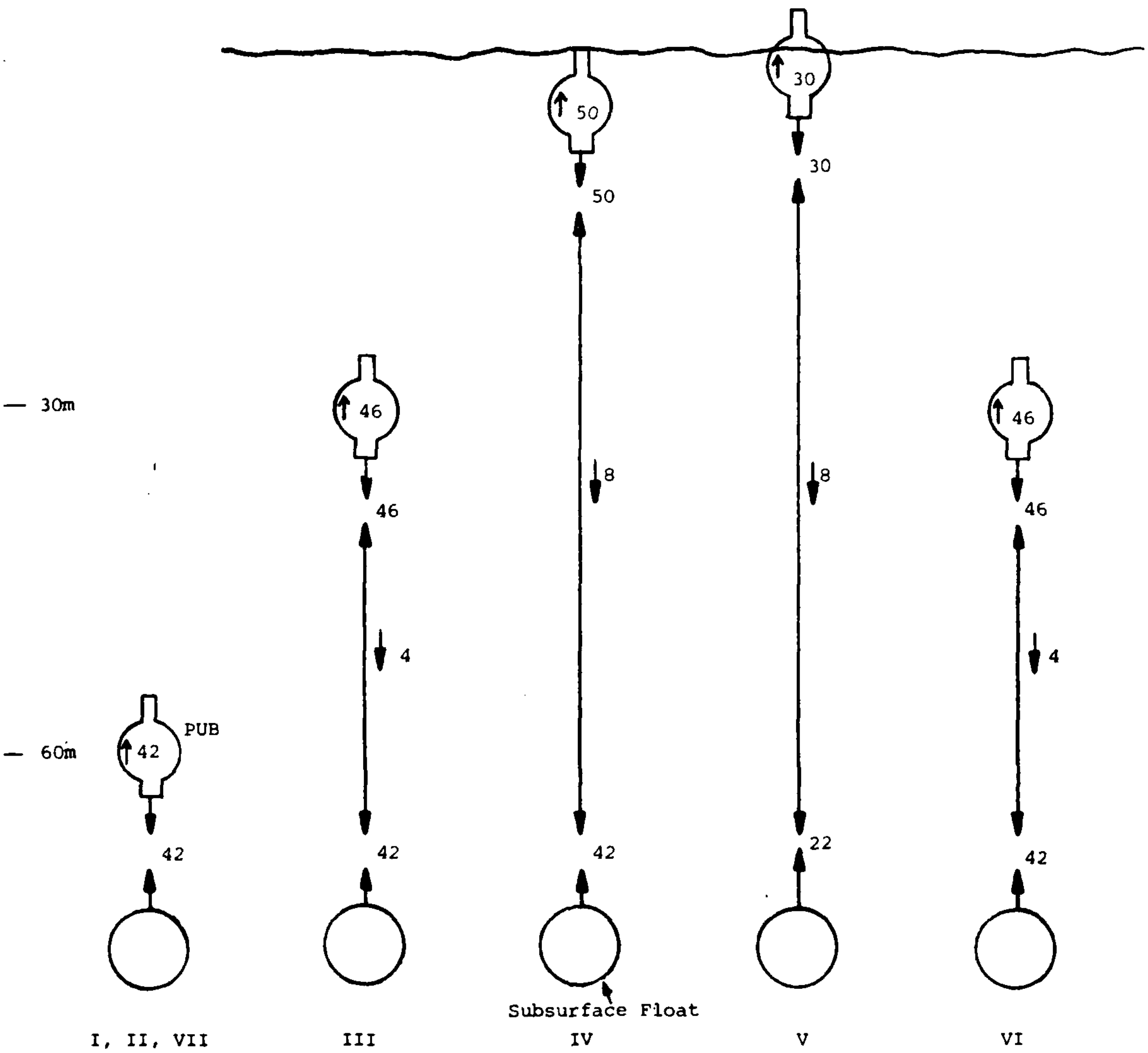



Figure 4.6 - Winch PUB Force Diagrams

- Case 2; No Current; No Waves and $\dot{z} = \pm 30$ cm/sec
- All Forces in Lbs

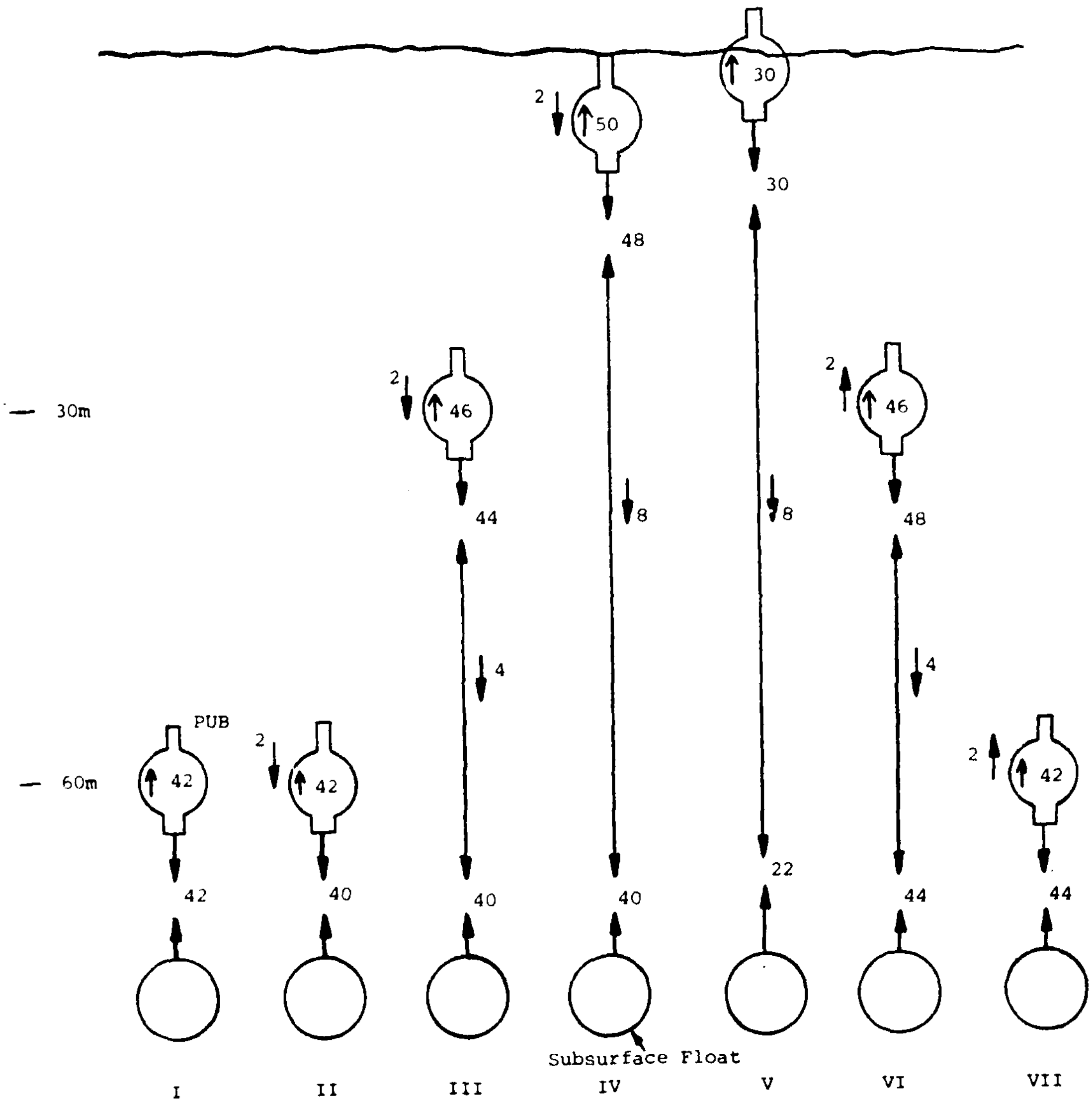



Figure 4.7 - Winch PUB Force Diagrams

- Case 3; No Waves; Current = 61 cm/s and $\dot{z} = \pm 30$ cm/s

- All Forces in Lbs

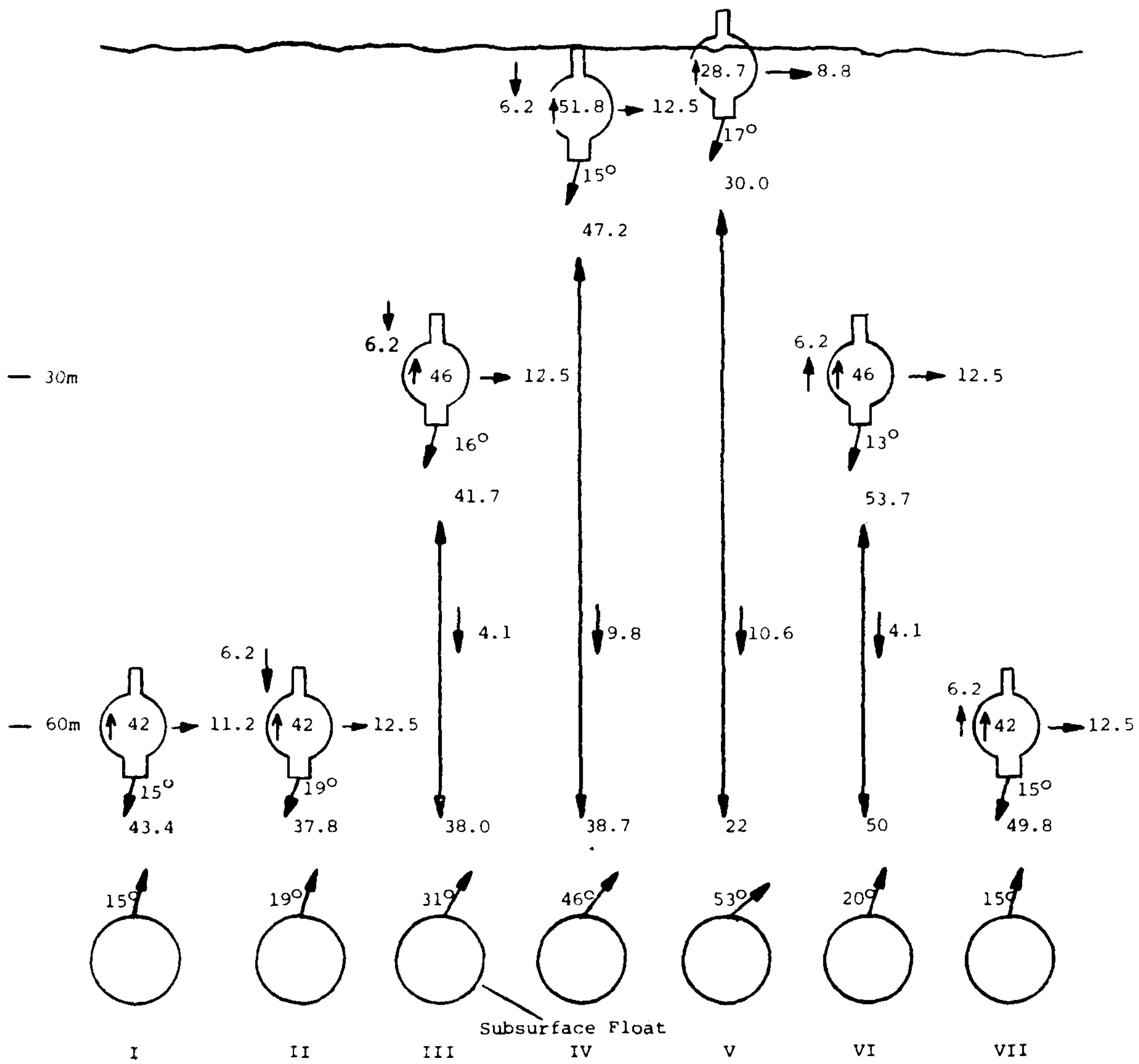



Figure 4.8 - Winch PUB Force Diagrams

- Case 1; No Current; No Waves and $\dot{z} = 0$
- All Forces are in Lbs

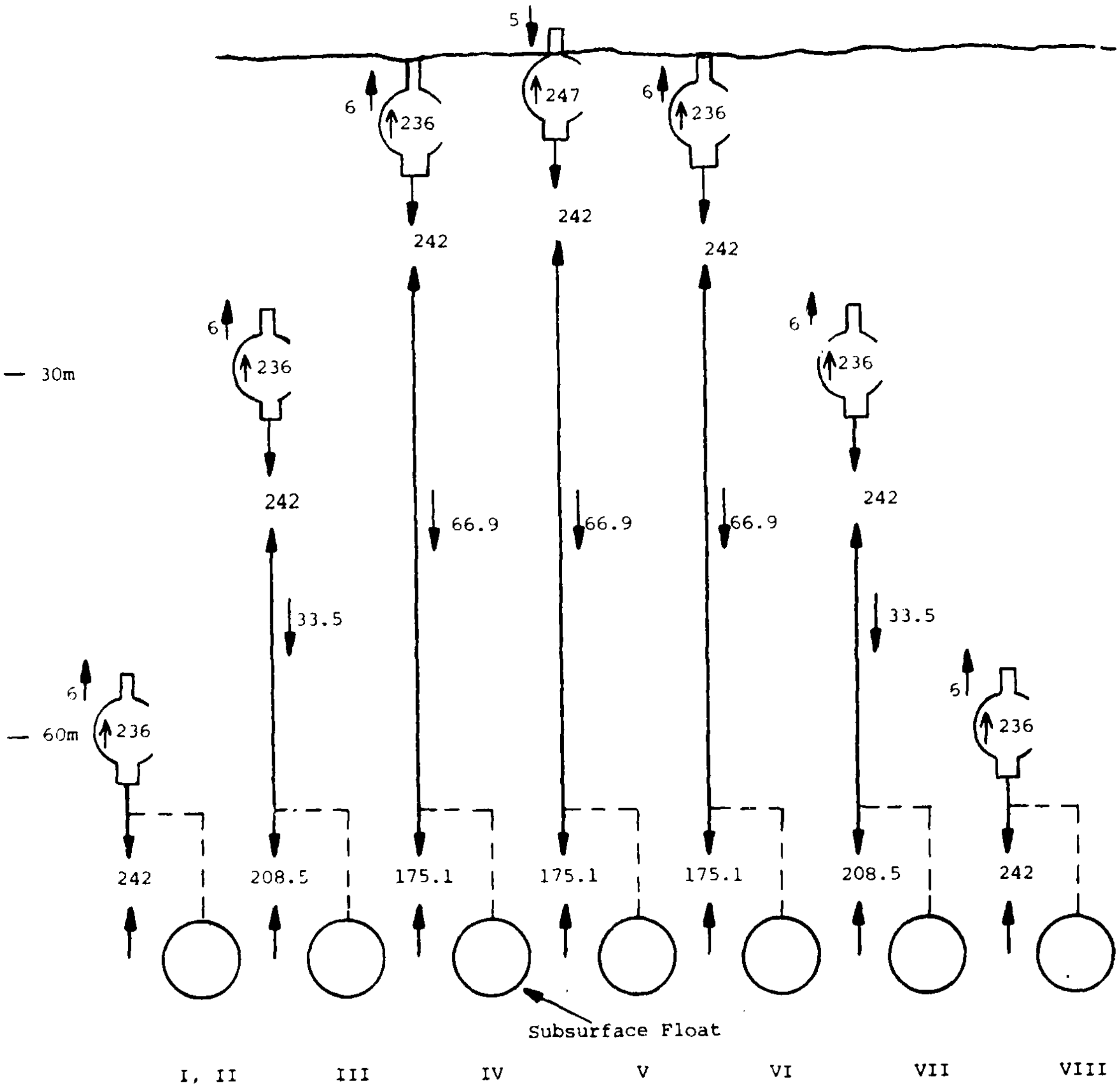



Figure 4.9 - Variable Buoyancy PUB Force Diagrams

- Case 2; No Current; No waves; $\dot{z} = \pm$ 30 cm/sec
- All Forces are in Lbs

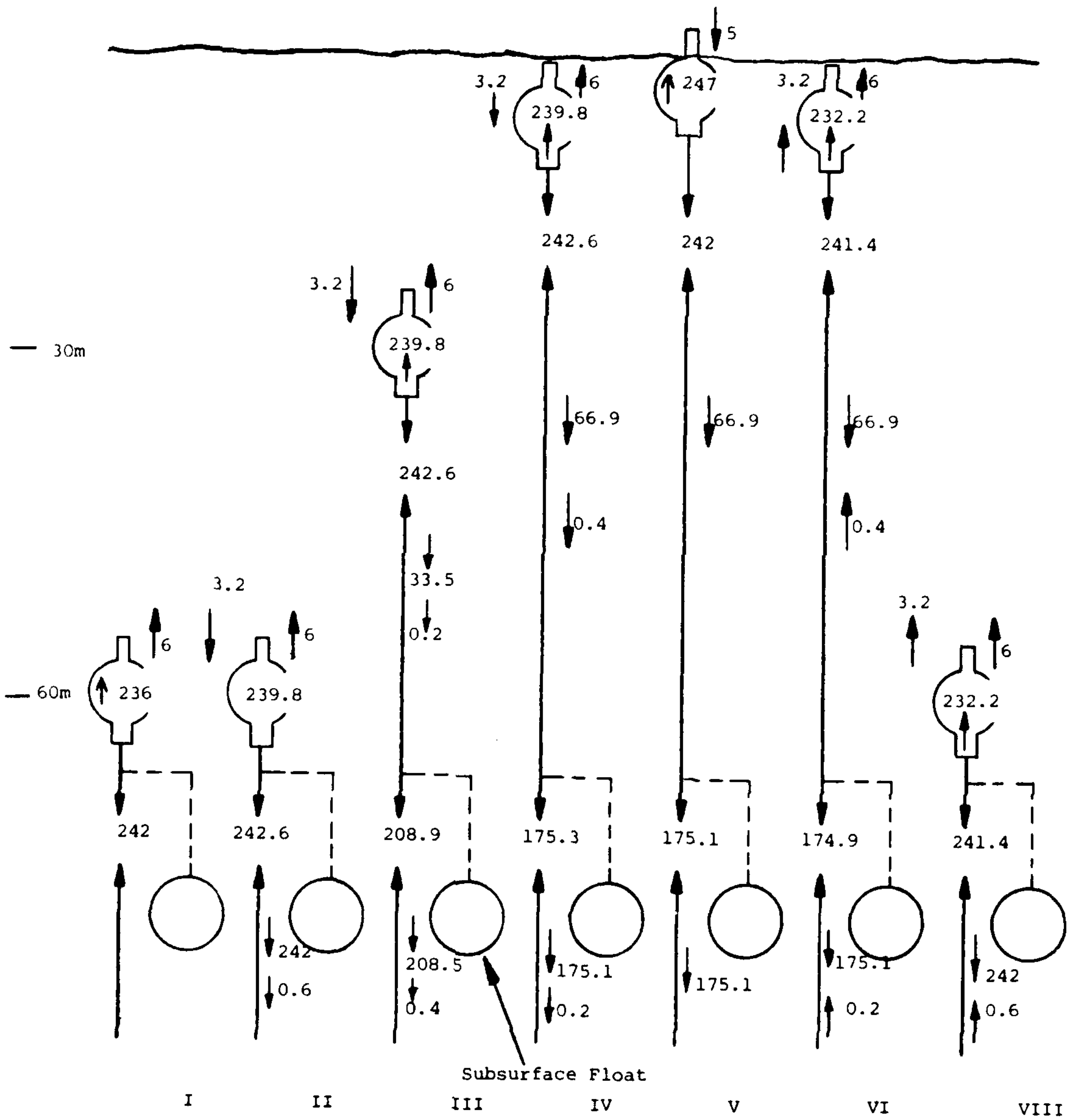



Figure 4.10 - Variable Buoyancy PUB Force Diagrams

- Case 3; No Waves; 61 cm/s Current; $\dot{z} = \pm$ 30 cm/sec
- All Forces are in Lbs

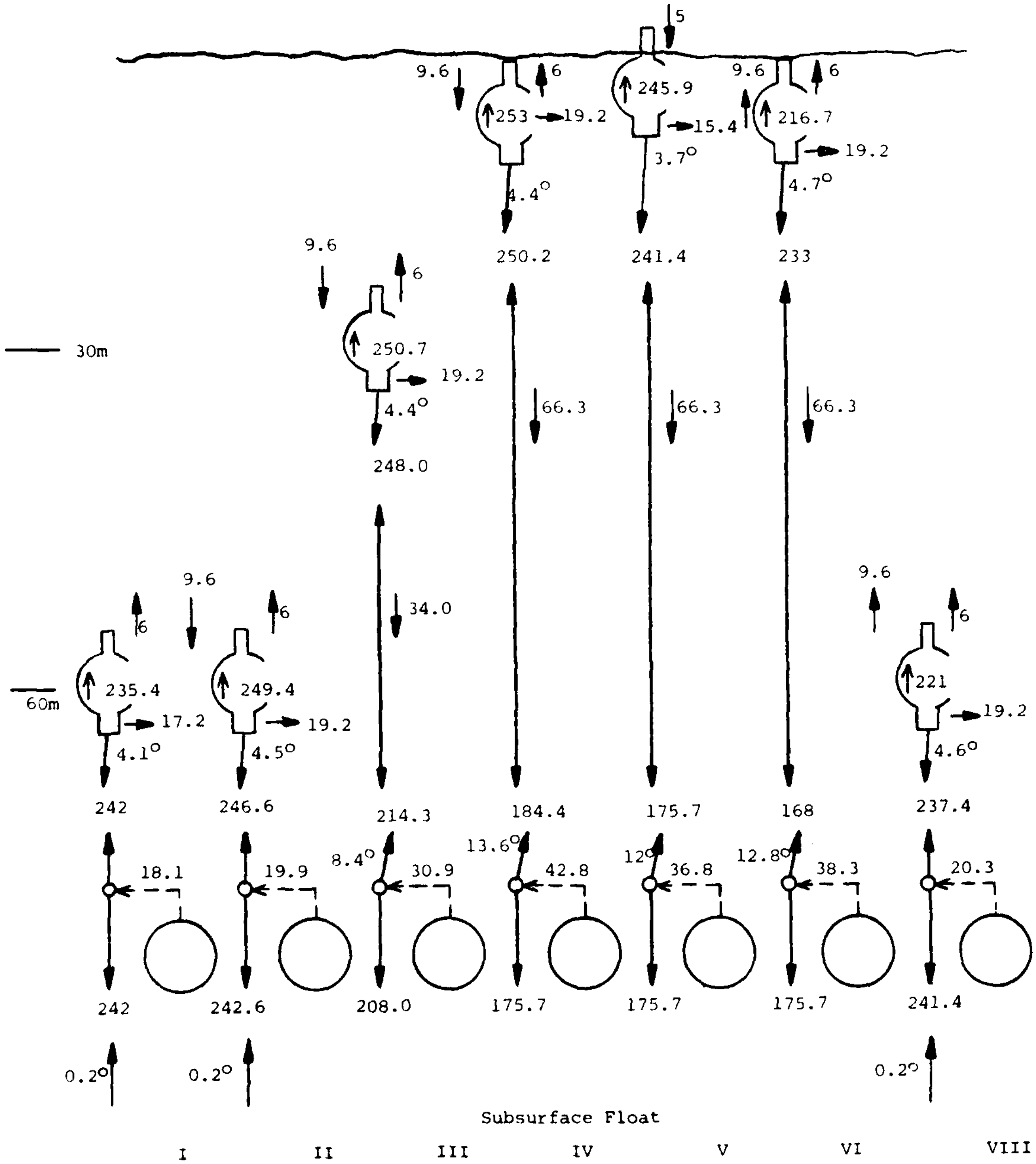



Figure 4.11 - Variable Buoyancy PUB Force Diagrams

## SECTION 5

## ALTERNATE DESIGN

Figure 5.1 shows an outline drawing of an alternate type of PUB which operates on a variable buoyancy principle.

This PUB can vary its buoyancy over a 260 N range by transferring 25 liters of silicone oil back and forth between internal and external bladders. An electric pump transfer system working at 33% efficiency causes the buoy to rise by moving oil from the internal bladder to the external bladder at ambient sea pressure. The buoy is made to sink by simply valving oil to the low pressure internal bladder. The motor drive battery must store 1.4 KWH for a 200-cycle mission (9 lbs. of lithium batteries).

The buoy is tethered by a long chain reeved through a fairlead gimballed about a vertical axis on the subsurface buoy. The gimballed fairlead and the chain tether were both selected to minimize the risk of fouling between the tether and the mooring line. Except for the external bladder, all components of the buoyancy control system are packaged within a 76 cm diameter spherical housing. The external bladder could be molded from NOFOUL rubber if necessary to prevent damage due to biofouling. Other aspects of the mechanical and electronic design are similar to the winch PUB design. Total deck weight of the variable buoyancy PUB is 1560 N (350 lbs) for the housing plus 1340 N (300 lbs) for the chain.

No significant difference exists between the unit production costs estimated for each configuration. Selection of the better approach must therefore be based upon operational benefits and development costs.

The winch PUB is smaller, lighter, easier to handle and deploy, and therefore more likely to be sought after by the user community. The variable buoyancy PUB, however, is mechanically simpler and, except for one feature, would be easier to develop. This questionable feature is the chain tether. We have not been able to convince ourselves that the tether can be trusted not to foul the mooring line. The problem is difficult to simulate on the computer because there are so many possible time-varying current profiles to try. It is difficult to resolve experimentally because the gear would have to be exposed to a number of "typical" environments. If we could find a foul-proof way to store the tether chain, or if we could show that a fouled chain can be pulled free by the buoyant sphere, then the choice would be more difficult. But as it stands the winch PUB is the better choice.

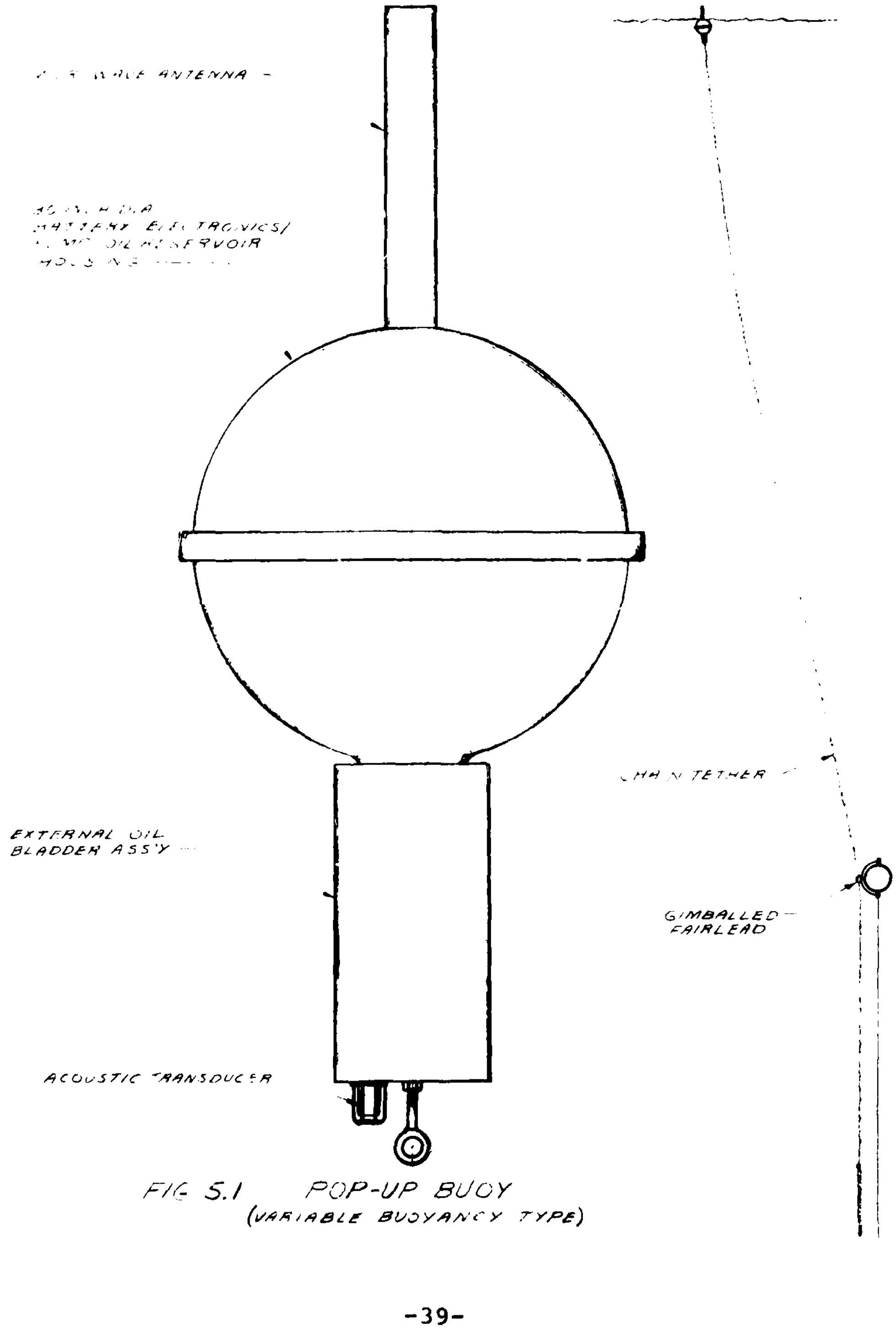



FIG 5.1 POP-UP BUOY
(VARIABLE BUOYANCY TYPE)

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